ReNew100
Demonstrate Resilient Power System Operation with 100% Non-Synchronous Generation

Ulrich Muenz

Siemens Corporate Technology, Princeton, NJ

100% renewable, non-synchronous generation poses big challenges to power system operation and planning

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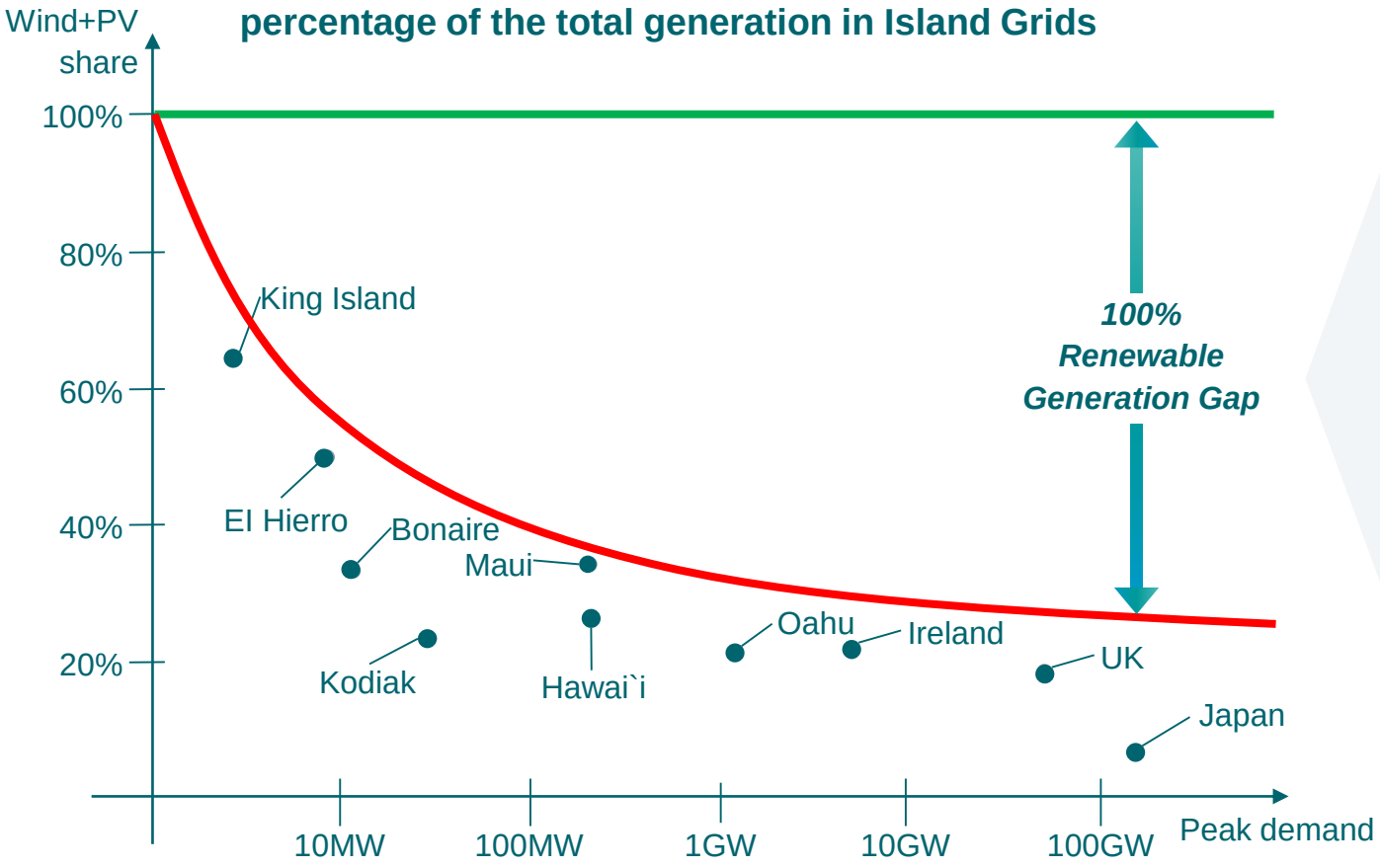
Electricity generation from wind & solar PV as a percentage of the total generation in Island Grids



Challenge	HW Solution	SW Solution
Power balance	Storage	Generation & demand management
Power transfer	Power lines	Nodal prices, OPF
Dynamic security	? **ReNew 100**	Dynamic Security Optimization
Protection	Breakers	Adaptive protection

Data from:
RMI Renewable Microgrids: Profiles from islands and remote communities across the globe
http://euanmearns.com/el-hierro-second-quarter-2018-performance-update/
http://euanmearns.com/a-first-look-at-the-king-island-tasmania-renewable-energy-integration-project/
https://www.nrel.gov/docs/fy15osti/64119.pdf
https://www.eenews.net/stories/1060038577
https://www.hawaiianelectric.com/clean-energy-hawaii/clean-energy-facts/about-our-fuel-mix
http://www.eirgridgroup.com/site-files/library/EirGrid/Generation_Capacity_Statement_20162025_FINAL.pdf
https://www.renewable-ei.org/en/statistics/electricity/
https://www.gov.uk/government/collections/electricity-statistics

OPF:Optimal Power Flow

ReNew100: Demonstrate N-1 Secure Power System Operation with 100% Non-Synchronous Generation

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Dynamic Security Optimization

Operator Support System

Dynamic Security Optimization

SIGUARD
Dynamic Security Assessment

EMS

Spectrum Power EMS

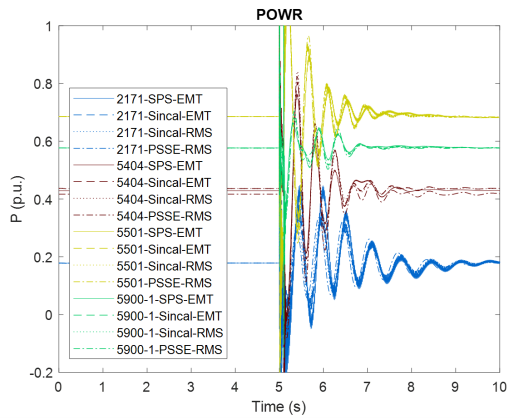
State Estimator | AGC

Minimize required grid-forming ratio

Consistent modeling across different tools

PSS®E | PSS® Sincal | SimPower Systems | Linear model

SIGUARD DSA | OPAL-RT | Dyn. Sec. Optimiz.



Power System

Model Calibration using HECO PMU data

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Modification of Hawai`i Island's power system leads to a power system with various 100% non-synchronous generation cases

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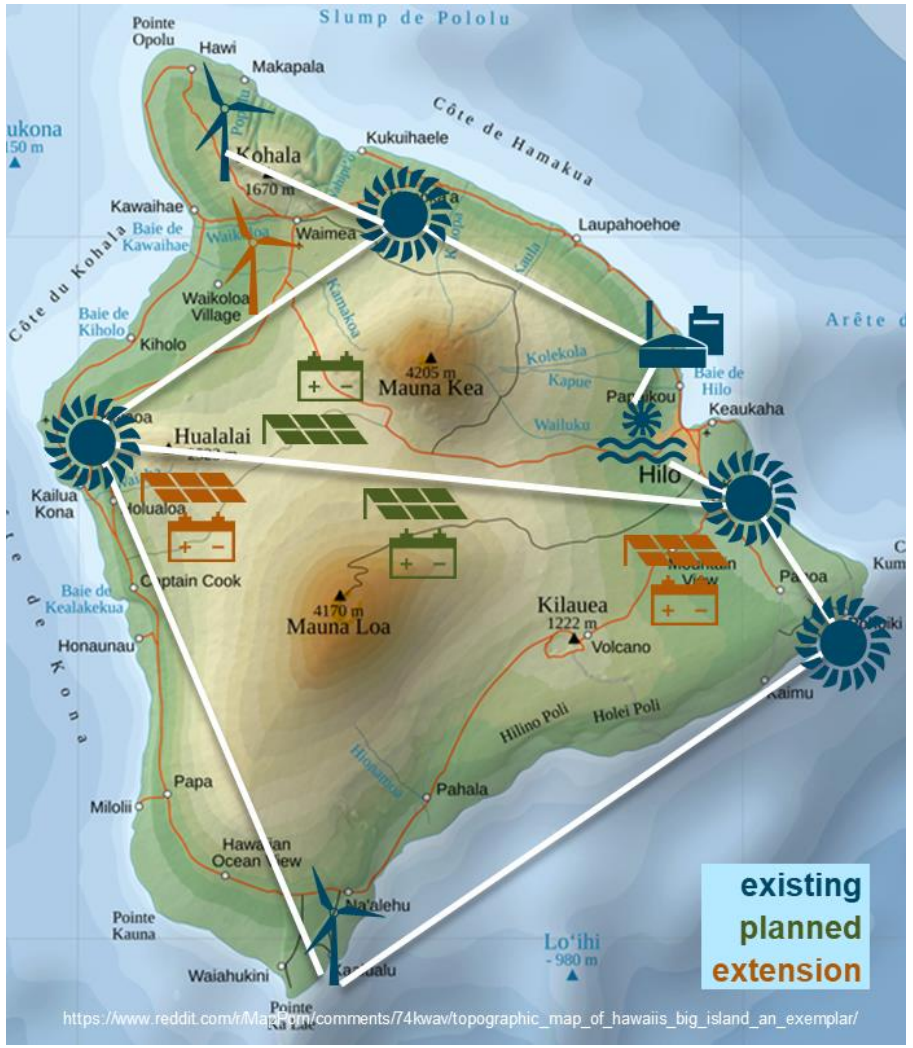
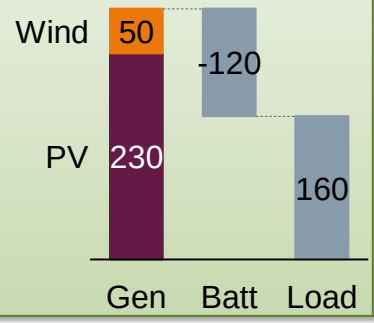
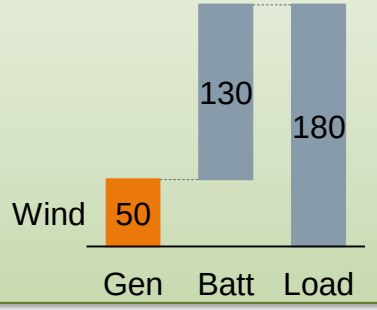
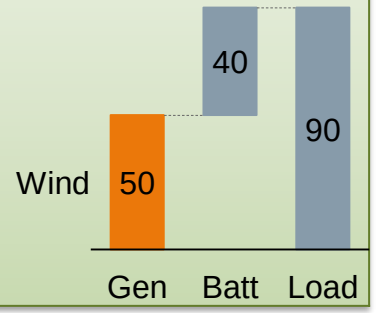


Generation	Today	Planned	Extension	Total
Wind	30MW		20MW	50MW
Centralized Solar		2x30MW	2x30MW	120MW
Distributed Solar	70MW		40MW	110MW
Centralized Battery		2x30MW	2x30MW	120MW
Distributed Battery			40MW	40MW
Synchr. Renewable	90MW			90MW
Conventional	160MW			160MW

	Noon	Evening	Night
Load	160MW	180MW	90MW
100% non-sync dispatch			

We develop consistent models across different simulation tools

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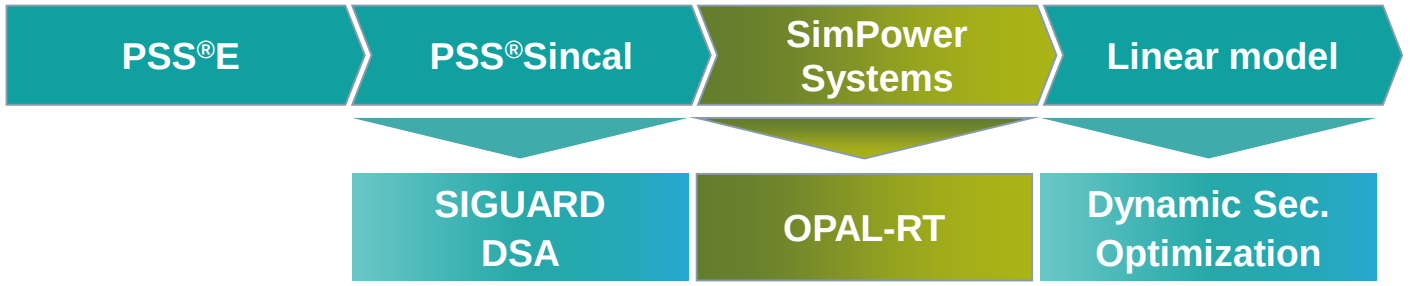

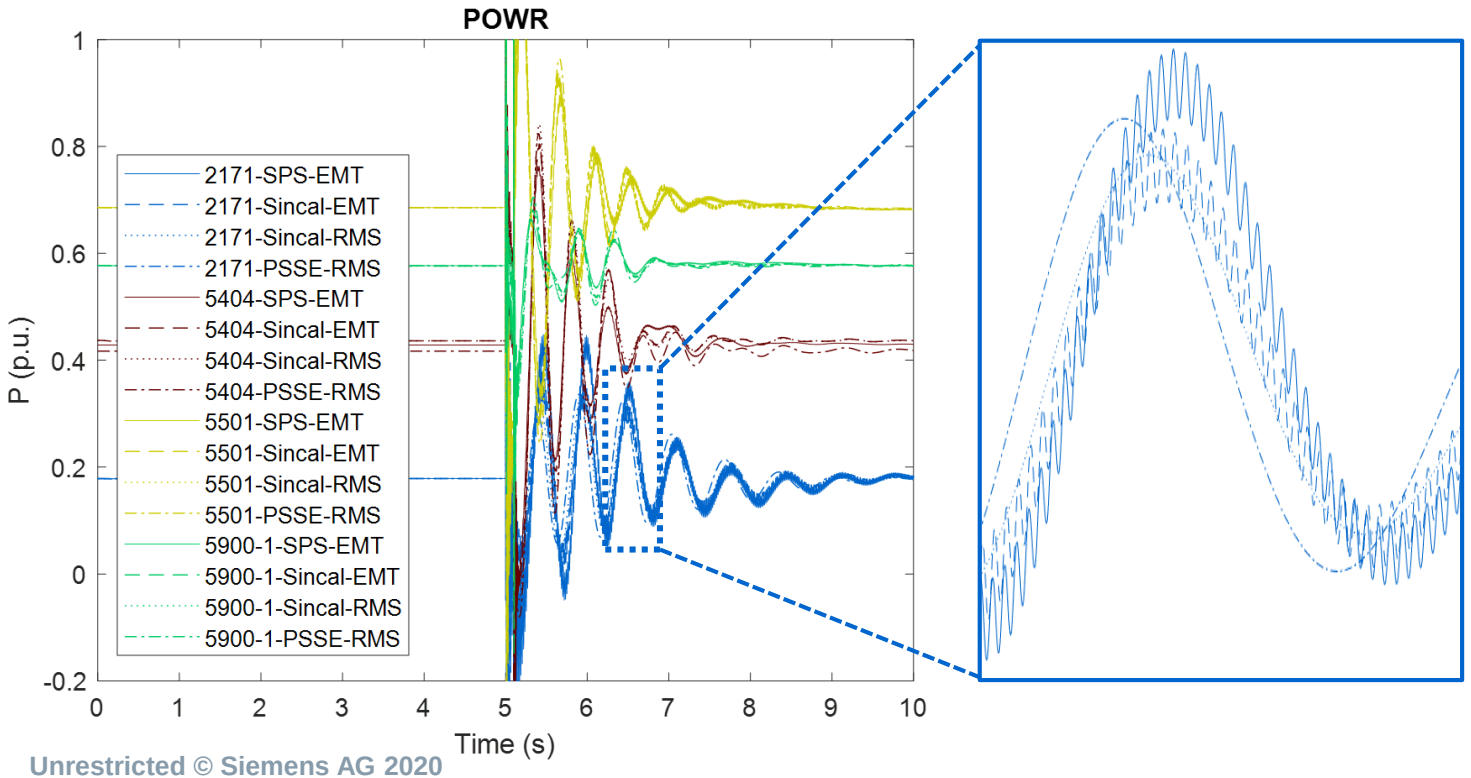

Project status

- 6 area, 10 generator model implemented
- extension to full model on-going

Compared models

- PSS®E (RMS)
- PSS®Sincal (RMS)
- PSS®Sincal (EMT)
- SimScape SimPower Systems (EMT)

Key observations from 6a/10g model

- **Very good match of key dynamics** between all models in both RMS and EMT
  - Eigenmodes
  - Overshoot
- **60 Hz oscillation** occurs in EMT simulation due to DC part of the stator dynamics.

ReNew100: Demonstrate N-1 Secure Power System Operation with 100% Non-Synchronous Generation

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Minimize required grid-forming ratio

Consistent modeling across different tools

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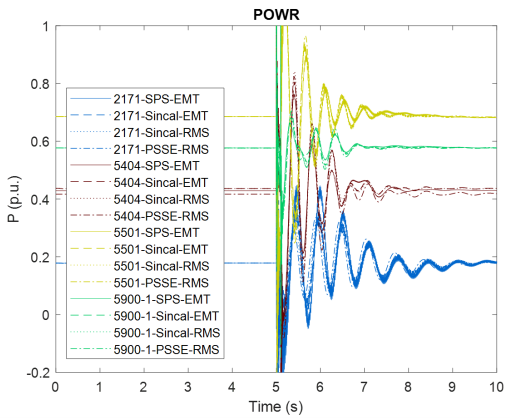
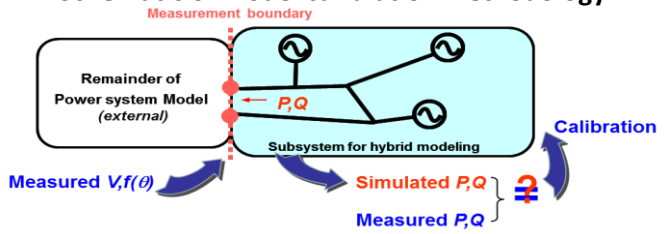
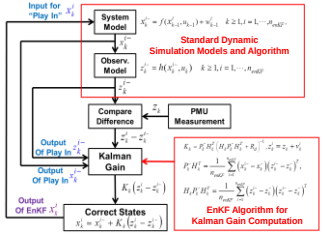


Power System

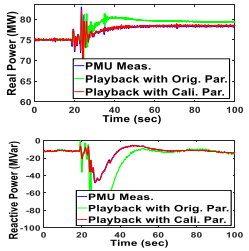
Model Calibration using HECO PMU data

Schematic of model calibration methodology





Ensemble Kalman Filter based model calibration algorithm



Model validation against PMU measurements

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We calibrate generator models using PMU data from HELCO

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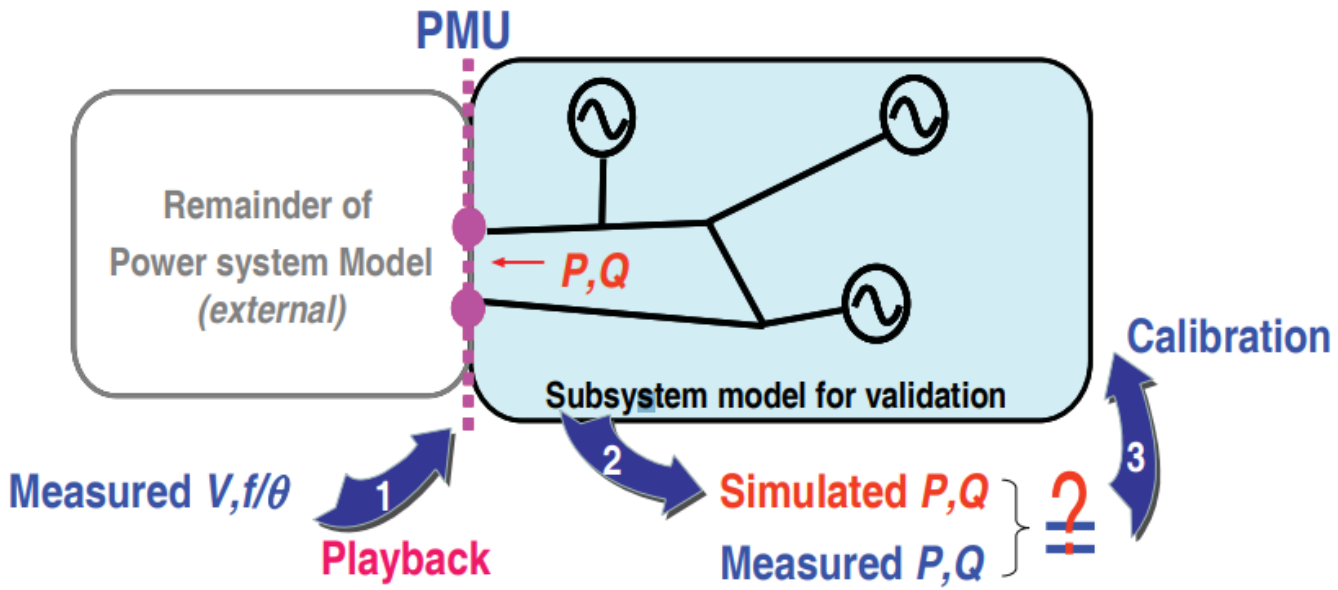
Challenge

- Accurate model required for Dynamic Security Assessment and Optimization
- Planning models used for generator plants may have incorrect parameters

Our Approach

- Calibrate power system model using PMU data from HELCO
- Generator model calibration based on Ensemble Kalman Filter (EnKF)
- PMU measurements will be used as event playback



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Dynamic Security Optimization

Nonlinear RMS model

$$\dot{\mathbf{x}} = f(\mathbf{x}, \mathbf{w}, \mathbf{K})$$
$$0 = h(\mathbf{x}, \mathbf{w}, \mathbf{K})$$

Linear RMS model

$$\dot{\mathbf{x}} = A(\mathbf{K})\mathbf{x} + B(\mathbf{K})\mathbf{w}$$
$$\mathbf{y} = C\mathbf{x}$$

H-inf Optimization

$$\min_{P=P^T\succ 0, \mathbf{K}, \gamma \in \mathbb{R}} \gamma$$
$$\begin{pmatrix} A(\mathbf{K})^T P + PA(\mathbf{K}) + C^T C & PB(\mathbf{K}) \\ B(\mathbf{K})^T P & -\gamma \mathbb{I} \end{pmatrix} \prec 0$$

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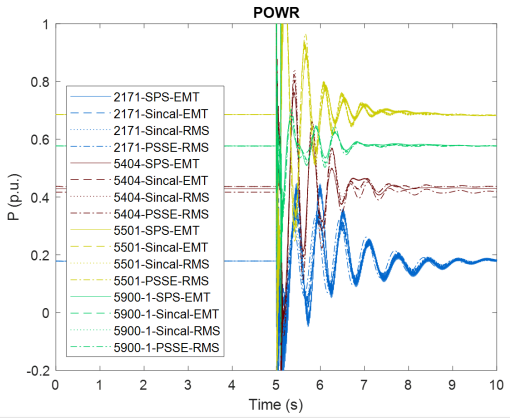
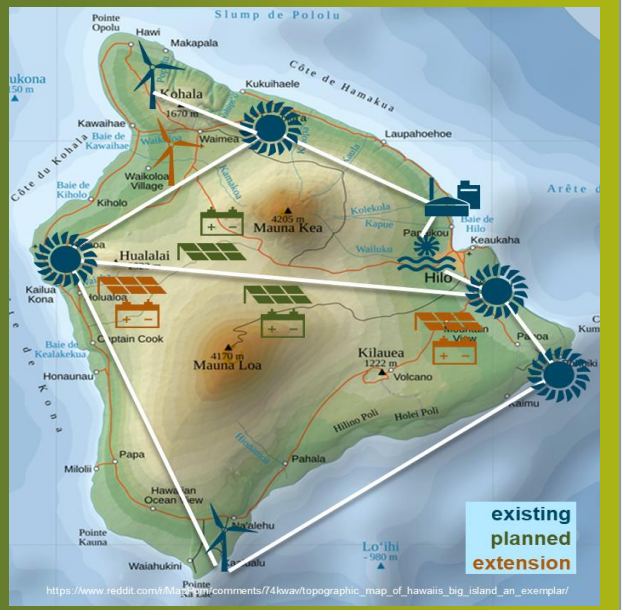
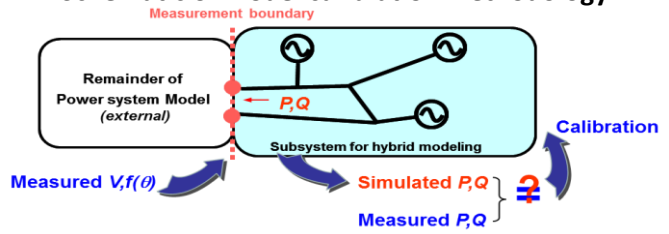


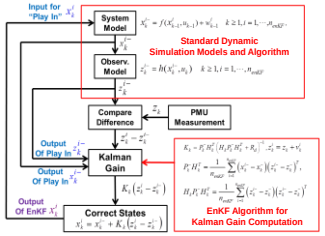
Power System



Model Calibration using HECO PMU data

Schematic of model calibration methodology





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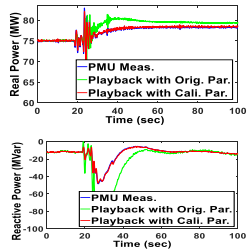

Model validation against PMU measurements

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We develop fast optimization algorithms for oscillation and overshoot damping

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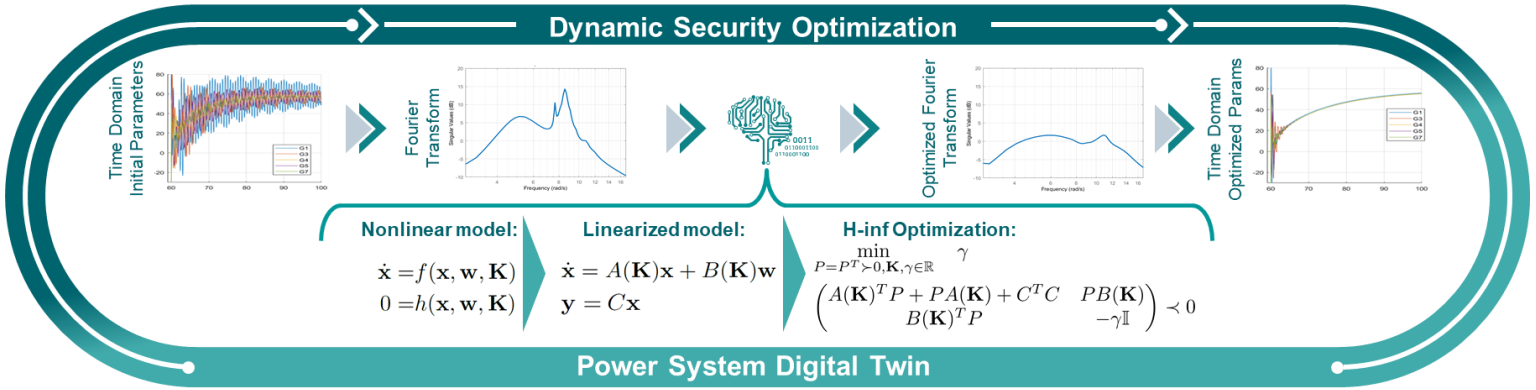
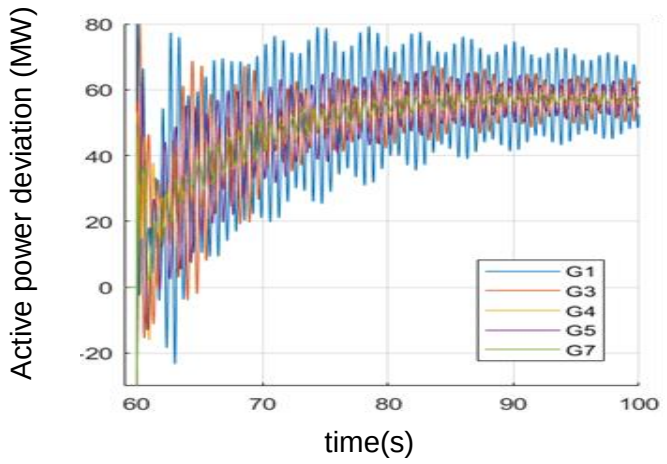


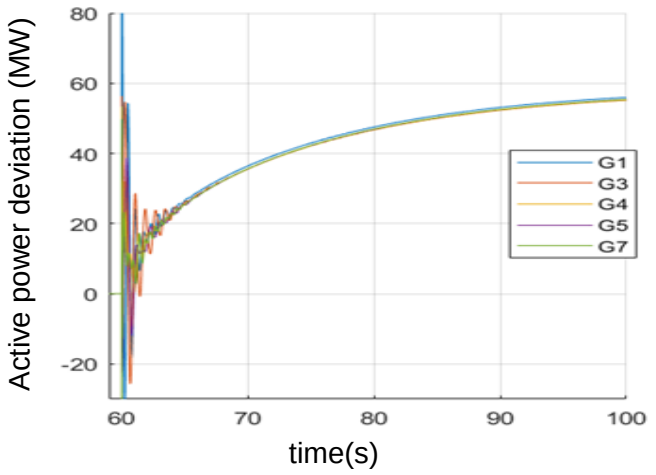
Project status

- Development of linear model started
- Optimization will developed starting from prior project's work

High risk of blackout



Resilient operation



From small to large

- **203x USA (1000GW)**
- **202x Puerto Rico (3GW)**
- **2022 Hawaii (180MW)**
- **2021 NSGB (20MW)**
- ✔ **2018 Galapagos (1MW)**
- ✔ **2017 IREN2 (0.1MW)**

NSGB: Naval Station Guantanamo Bay

Detailed power plant models are optimized

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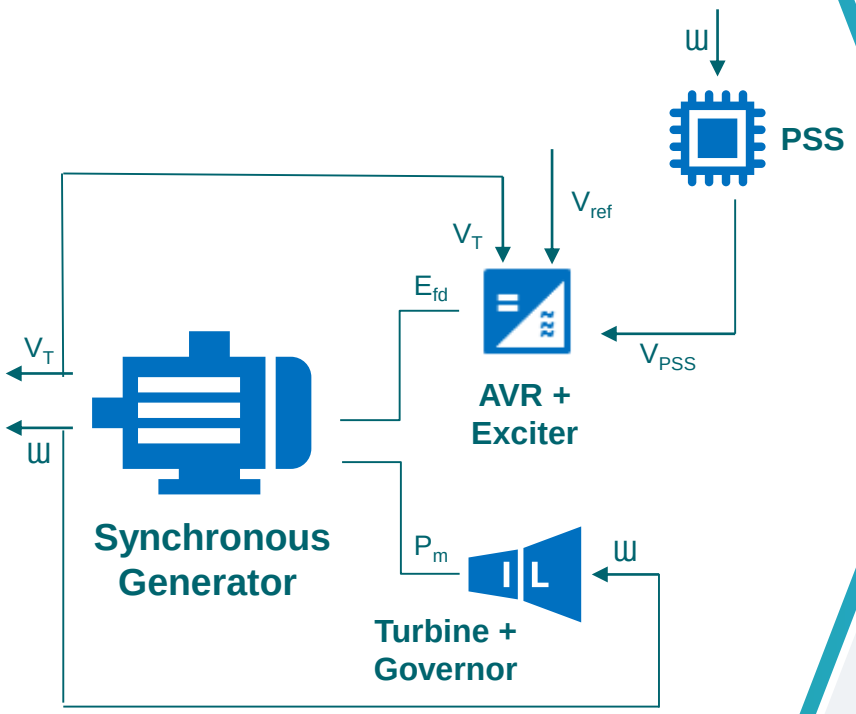
❖ *19 states per generator*

❖ *10 tunable controller parameters per generator*

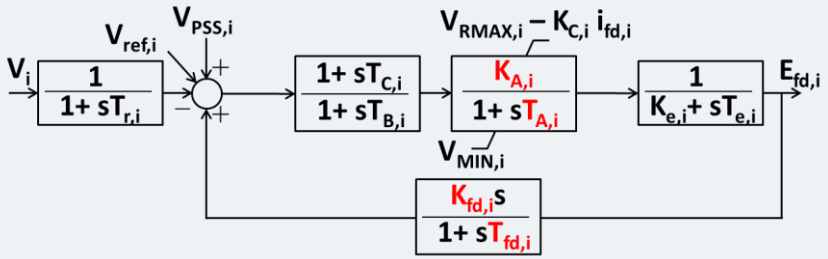
Decomposition of Generator



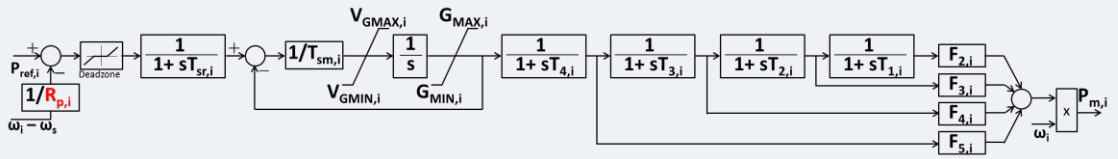
PSS

$$\omega_i - \omega_s \rightarrow \frac{1}{1+sT_{s,i}} \rightarrow K_{S,i} \rightarrow \frac{sT_{w,i}}{1+sT_{w,i}} \rightarrow \frac{1+sT_{1,i}}{1+sT_{2,i}} \rightarrow \frac{1+sT_{3,i}}{1+sT_{4,i}} \rightarrow V_{PSS,i}$$

Automatic Voltage Regulator
+ Exciter Model



Turbine + Governor



Turbine + Governor

Application example shows significant increase of power oscillation damping for IEEE39 benchmark model

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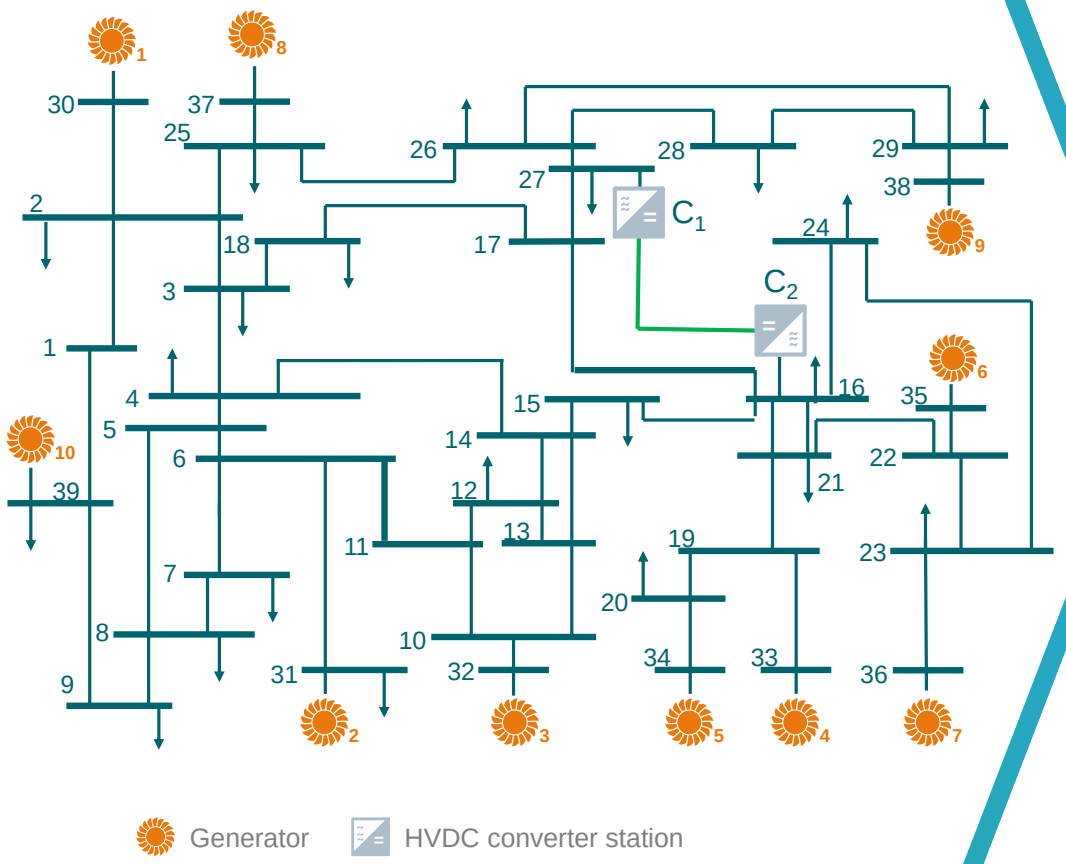
IEEE 39 bus benchmark model



IEEE 39 bus model from[3] with component models from[4,5] and PSS from[2]

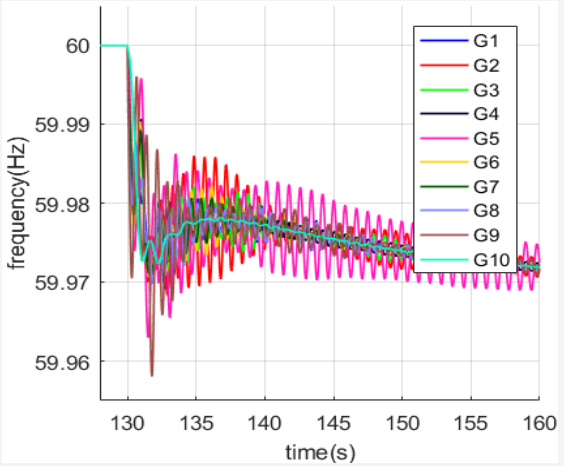
add'l HVDC line

Optimization Problem Characterization

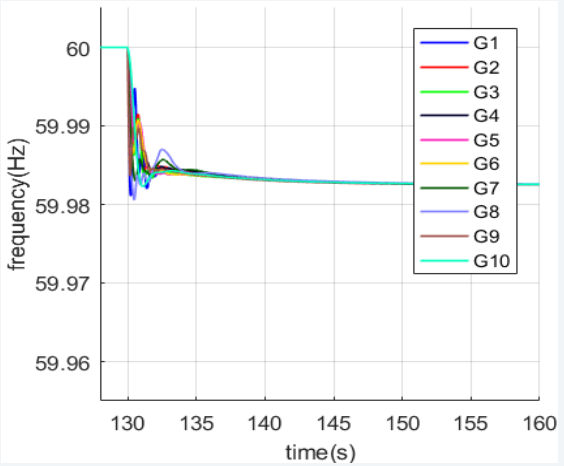
216 states

128 controller parameters

Initial Parameters



Optimized Parameters



[2] P. Kundhur, Power System Stability and Control, McGraw-Hill, 1993.
[3] A. Moeini, I. Kamwa, P. Brunelle, G. Sybille, "Open Data IEEE Test Systems Implemented in SimpowerSystems for Education and Research in Power Grid Dynamics and Control," Power Engineering Conference (UPEC), 2015 50th International Universities, 1-4 Sept. 2015, Staffordshire University, UK. (https://www.mathworks.com/matlabcentral/fileexchange/54771-10-machine-new-england-power-system-ieee-benchmark)
[4] IEEE committee report, "Dynamic models for steam and hydro turbines in power system studies," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-92, No. 6, 1973, pp. 1904-1915.
[5] "Recommended Practice for Excitation System Models for Power System Stability Studies," IEEE® Standard 421.5-1992, August, 1992.

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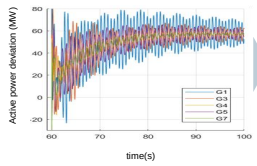
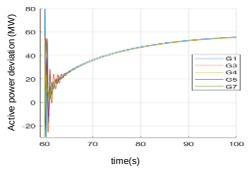
Dynamic Security Optimization

Initial paramaters



Optimized parameters



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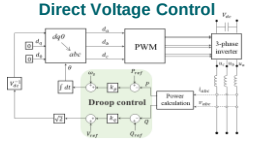
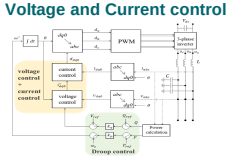
Minimize required grid-forming ratio

Compare grid-forming inverter controls to achieve N-1 resilient operation with minimal ratio between grid-forming and grid-supporting inverters

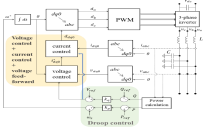
Direct Voltage Control



Voltage and Current controls



Voltage and Current control with voltage feed-forward



Consistent modeling across different tools

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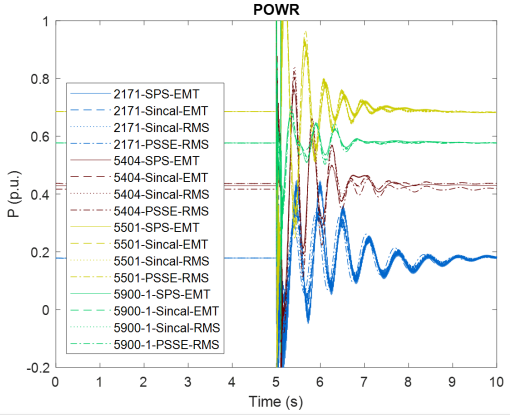
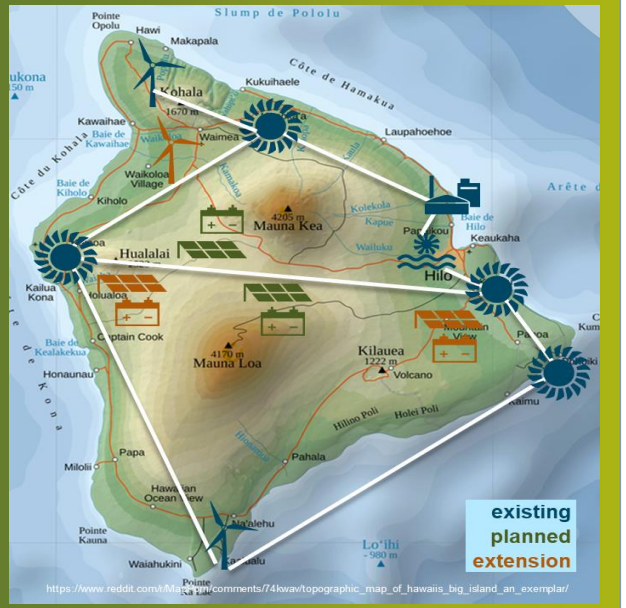
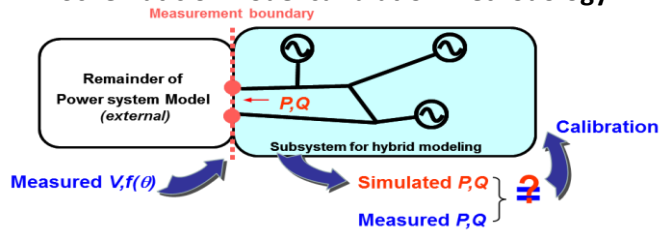


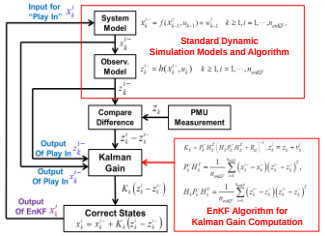
Power System



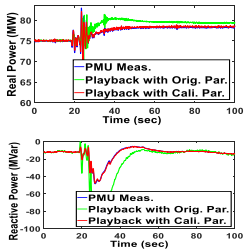
Model Calibration using HECO PMU data

Schematic of model calibration methodology





Ensemble Kalman Filter based model calibration algorithm



Model validation against PMU measurements

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Hawaiian Electric Company

U.S. DEPARTMENT OF ENERGY

arpa·e CHANGING WHAT'S POSSIBLE

We benchmark grid-forming and grid-supporting inverter control structures to minimize grid-forming to grid-supporting ratio

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Challenge

- Minimize required ratio between grid-forming inverters and grid-following inverter for N-1 secure operation

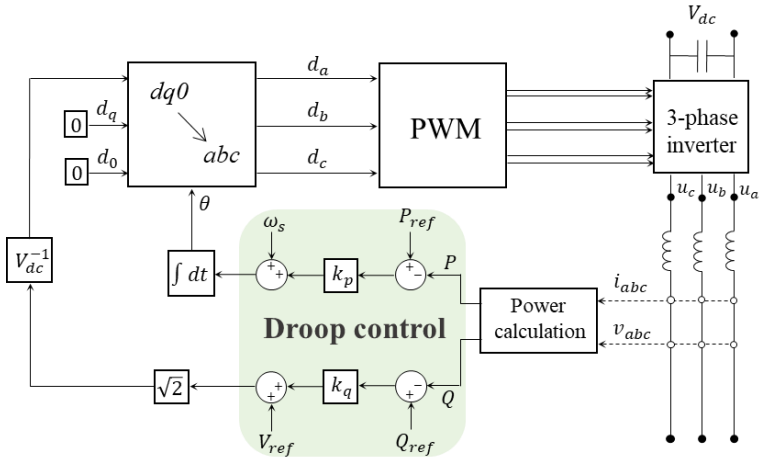
Our Approach

- Benchmark grid-forming and grid-following inverter controllers
- Validate N-1 secure operation in PSS®Sincal

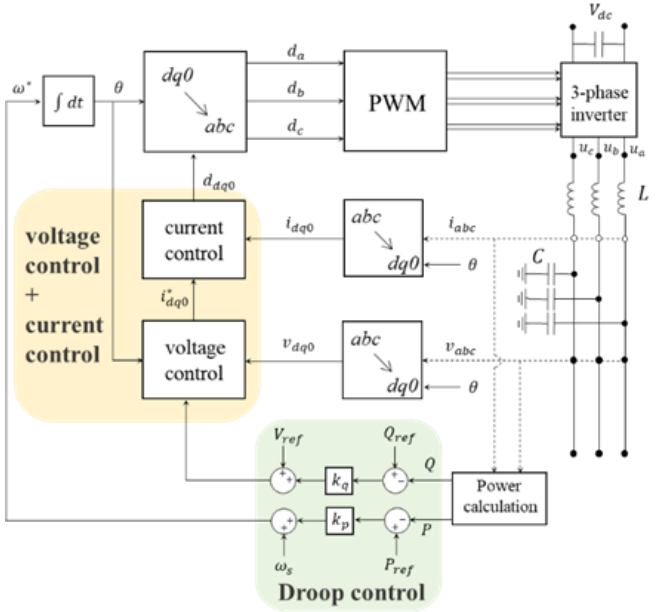
Project status

- Development of PSS®Sincal model started

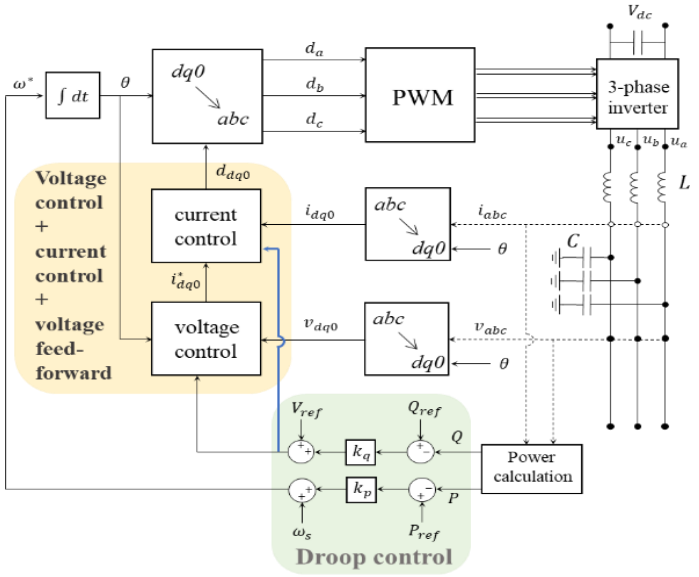
Direct Voltage Control



Voltage and Current controls



Voltage and Current control with voltage feed-forward



ReNew100: Demonstrate N-1 Secure Power System Operation with 100% Non-Synchronous Generation

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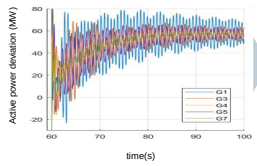
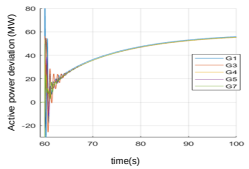
Dynamic Security Optimization

Initial paramaters



Optimized parameters



Nonlinear RMS model

$$\dot{\mathbf{x}} = f(\mathbf{x}, \mathbf{w}, \mathbf{K})$$
$$0 = h(\mathbf{x}, \mathbf{w}, \mathbf{K})$$

Linear RMS model

$$\dot{\mathbf{x}} = A(\mathbf{K})\mathbf{x} + B(\mathbf{K})\mathbf{w}$$
$$\mathbf{y} = C\mathbf{x}$$

H-inf Optimization

$$\min_{P=P^T\succ 0, \mathbf{K}, \gamma \in \mathbb{R}} \gamma$$
$$\begin{pmatrix} A(\mathbf{K})^T P + PA(\mathbf{K}) + C^T C & PB(\mathbf{K}) \\ B(\mathbf{K})^T P & -\gamma \mathbb{I} \end{pmatrix} \prec 0$$

Operator Support System

EMS

Dynamic Security Optimization

SIGUARD Dynamic Security Assessment

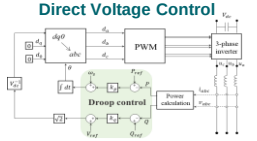
Spectrum Power EMS

State Estimator | AGC

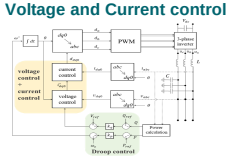
Minimize required grid-forming ratio

Compare grid-forming inverter controls to achieve N-1 resilient operation with minimal ratio between grid-forming and grid-supporting inverters

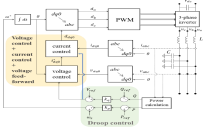
Direct Voltage Control



Voltage and Current controls



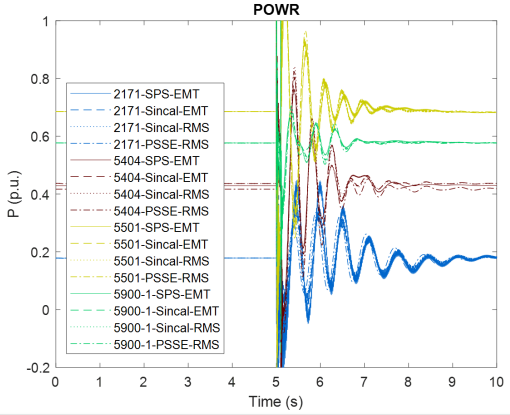
Voltage and Current control with voltage feed-forward



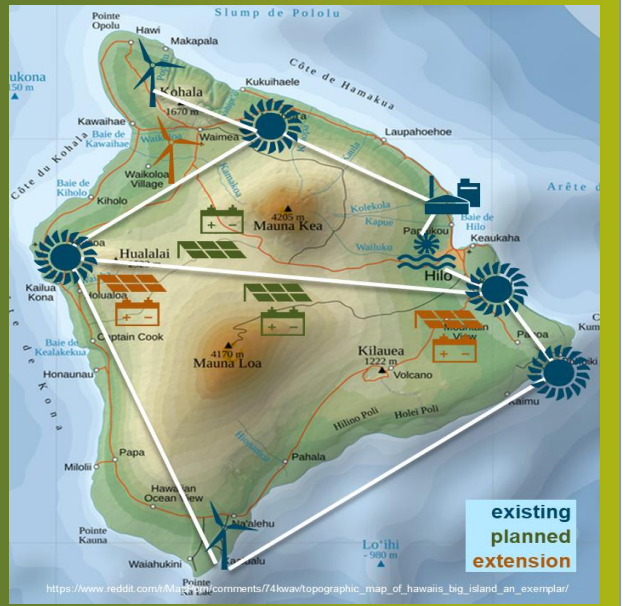
Consistent modeling across different tools

PSS®E | PSS® Sincal | SimPower Systems | Linear model

SIGUARD DSA | OPAL-RT | Dyn. Sec. Optimiz.

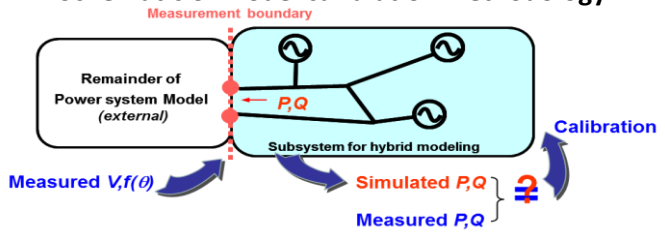


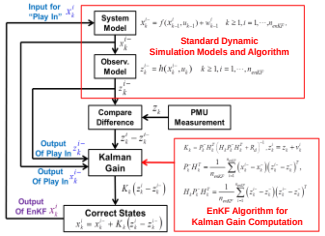
Power System



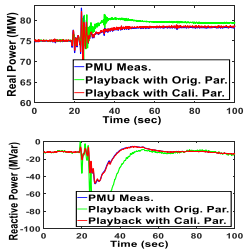
Model Calibration using HECO PMU data

Schematic of model calibration methodology





Ensemble Kalman Filter based model calibration algorithm



Model validation against PMU measurements

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